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# Automated In Situ Observations of Upper Ocean Biogeochemistry, Bio-Optics, and Physics and Their Potential Use for Global Studies

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*Tommy D. Dickey, Timothy C. Granata,  
and Isabelle Taupier-Letage*

## Abstract

The processes controlling the flux of carbon in the upper ocean have dynamic ranges in space and time of at least nine orders of magnitude. These processes depend on a broad suite of inter-related biogeochemical, bio-optical, and physical variables. These variables should be sampled on scales matching the relevant phenomena. Traditional ship-based sampling, while critical for detailed and more comprehensive observations, can span only limited portions of these ranges because of logistical and financial constraints. Further, remote observations from satellite platforms enable broad horizontal coverage which is restricted to the upper few meters of the ocean. For these main reasons, automated subsurface measurement systems are important for the fulfillment of research goals related to the regional and global estimation and modeling of time varying biogeochemical fluxes. Within the past few years, new sensors and systems capable of autonomously measuring several of the critical variables have been developed. The platforms for deploying these systems now include moorings and drifters and it is likely that autonomous underwater vehicles (AUV's) will become available for use in the future. Each of these platforms satisfies particular sampling needs and can be used to complement both shipboard and satellite observations.

In the present review, 1) sampling considerations will be summarized, 2) examples of data obtained from some of the existing automated in situ sampling systems will be highlighted, 3) future sensors and systems will be discussed, 4) data management issues for present and future automated systems will be considered, and 5) the status of near real-time data telemetry will be outlined. Finally, we wish to make it clear at the outset that the perspectives presented here are those of the authors and are not intended to represent those of the United States JGOFS program, the International JGOFS program, NOAA's C&GC program, or other global ocean programs.

## Sampling Considerations

Development of in situ autonomous instrumentation has been driven in part by the need to increase the time and space domains of bio-optical and biogeochemical sampling. Many interdisciplinary studies require homologous data sets for a multiplicity of variables as well. In the past, sampling of hydrodynamical and biological (and biogeochemical) variables was generally achieved independently

(e.g., long term moorings of current meters, short term ship-based surveys with CTD casts and plankton net tows), although a few exceptions are noteworthy (e.g., from ships: Cullen et al., 1983; Smith et al., 1984; from the research platform R/P FLIP: Dickey et al., 1986). Because of the inconsistencies of temporal and spatial resolution and lack of concurrence among data sets, no common data processing technique could be strictly applied. As a result, any cross-interpretation of the non-coherent data sets was hampered, and it was difficult to get valuable information on the bio- and geo-dynamical relationships. In most cases, investigations were limited to qualitative aspects. Now, with multi-variable in situ autonomous systems, it is possible to obtain long term and high temporal resolution data sets, and to perform spectral, correlational, and coherence types of analyses of interdisciplinary data sets. However, no single automated in situ sampling device is sufficient. Ship and spaceborne measurements will still be necessary: 1) to check for the sensor drifts and calibrations, 2) to obtain high precision data, since autonomy usually implies a trade-off between sampling rate and measurement precision, 3) to obtain a comprehensive set of observations, including some variables which are still inaccessible to autonomous methods, and 4) to provide the temporal evolution of the spatial fields using a combination of in situ and satellite image time series.

The Joint Global Ocean Flux Study (JGOFS) program (sponsored by the National Science Foundation, NSF) addresses problems concerning the regional and global estimations of biogeochemical fluxes of materials, particularly carbon, across the air-sea interface, within the interior of the ocean, and at the seafloor (Brewer et al., 1986). Major study-types include: site specific long-term time series studies, regional process-oriented studies, and large scale (global) surveys (U.S. JGOFS Report 11, 1990). Modeling (U.S. GOFs Report 4, 1986; U.S. JGOFS Report 14, 1992) and data management (U.S. GOFs Report 8, 1988) are integral parts of the JGOFS program as well. Complementary studies including the National Oceanic and Atmospheric Administration's (NOAA's) Climate and Global Change (C&GC) program are also being conducted at this time (e.g., Sarachik and Gammon, 1989).

Automated in situ instrumentation is needed for various aspects of JGOFS and C&GC. The availability of automated systems is quite new to the bio-optical and biogeochemical community and the use of such systems for JGOFS and C&GC is in the initial phase at present (Dickey, 1991). One of the objectives of the JGOFS time series program is to determine long-term changes in key and relatively easily measured variables. For physical climate change, temperature is obviously a crucial variable. In terms of biogeochemical and bio-optical changes, variables such as pCO<sub>2</sub>, pH, dissolved oxygen, water clarity, pigment biomass, and phytoplankton productivity are some of the critical quantities. The unambiguous interpretation of measurements used to determine these quantities remains a challenge, however, considerable progress in making high-resolution, long-term bio-optical and biogeochemical measurements has been made and rapid advancements in sensor and system development seem likely. Thus, automated sampling is not only important, but technologically feasible (e.g., Dickey, 1991; Autono-

mous Bio-optical Ocean Observing Systems [ABOOS] Scientific Symposium, 1992). Global scale changes cannot be determined solely from a limited number of time series sites. However, changes at specific sites can be used to monitor long-term trends in oceanic biogeochemical and bio-optical variables, just as the famous measurements at Mauna Loa have provided compelling evidence of atmospheric CO<sub>2</sub> concentration increases (Keeling and Whorf, 1990). Further, these sites can provide excellent opportunities for developing automated sampling systems which can be used at remote time series stations, as part of other JGOFS process-oriented studies, and potentially for long transect/large scale studies.

In terms of links to global observations, automated in situ systems are imperative. Remote sensing of ocean color and the derivation of upper ocean pigment biomass and primary productivity on regional and global scales will be done with the Sea Wide Field Sensor (SeaWiFS) color scanner from a satellite during the next few years (e.g., Yoder et al., 1988; Esaias et al., 1992; Hooker and Esaias, 1992). However, the requisite algorithms rely on in situ observations of bio-optical variables (e.g., Evans, 1992; Hooker and Esaias, 1992; Mueller and Austin, 1992). These observations need to be done in such a way that inconsistencies between satellite and in situ sensors and in temporal and spatial sampling scales can be interpreted and corrected. Additionally, satellite-based ocean color and temperature measurements are often obviated because of cloud or water vapor conditions. Further, the understanding and interpretation of fundamental measurements such as fluorescence remain problematic. Intensive and extensive shipboard sampling at mooring sites and over the world ocean will be important.

Within the next few years, it is possible that moorings may be used for both process-oriented regional studies (presently part of JGOFS and C&GC Equatorial Pacific study) and dedicated time series sites near Bermuda and Hawaii. In the more distant future, it is anticipated that additional time series sites may utilize automated systems deployed from moorings and autonomous underwater vehicles (AUV's). It is possible that drifters and AUV's may be used for improved global coverage as well as for process-oriented and survey studies (e.g., McLean et al., 1992; Olson, 1992; Hitchcock and Olson, 1992).

The development of AUV's is still underway, however their long-term potential for use in JGOFS and C&GC work seems great and their inclusion here seems well-justified. Moored and drifter measurements are presently more advanced and widespread at this point, thus greater emphasis will be placed on them. Time series observations of biogeochemical, bio-optical, and physical variables at present and future JGOFS time series sites and in regions of process-oriented studies are important for several reasons. Some of these are detailed below.

The processes controlling the flux of carbon in the upper ocean have dynamic ranges in space and time of at least nine orders of magnitude (Fig. 1; Dickey, 1991). These processes depend on oceanic biogeochemical, bio-optical, physical, and meteorological variables. These variables should be sampled on scales matching the relevant processes (e.g., aliasing problem: Nyquist sampling theory). Ship-

based sampling, while critical for detailed and more comprehensive observations, can span only a limited portion of these ranges because of logistical and financial constraints (Figs. 1 and 2). For example, data collected from present JGOFS time series sites near Bermuda (Knap et al., 1990; Michaels and Knap, 1992; Michaels et al., 1992) and Hawaii (Karl and Winn, 1991) as well as programs elsewhere (e.g., coastal waters off Long Island, New York: Whitledge and Wirick, 1983, 1986, Medeiros and Wirick, 1992; off Los Angeles: Dickey and Manov, 1991 and work in progress; in Monterey Bay, Chavez et al., 1992); Sargasso Sea and near Iceland: Dickey et al., 1991; 1992a,b; Dickey, 1991; Marra et al., 1992) indicate that variability in key derived quantities such as pigment biomass and primary productivity often occurs on time scales of days or less. This variability results from local, advective, or various mixes of local and advective phenomena. It is important to note that the problems being addressed are nonlinear in nature and episodic forcing and responses probably contribute large proportions of the variance (e.g., Dickey et al., 1991; Dickey et al., 1992a,b). Thus, it is important that high-resolution time series data (including currents) be collected concurrently at the sites and that horizontal/vertical spatial data be collected in the vicinity of the sites. Fortunately, it is now possible to do measurements of several of the principle variables from moorings on time scales as short as 1 minute (e.g., Dickey, 1991).

Remote sensing of the very near surface ocean can provide important sea surface temperature, ocean color, and sea surface elevation data on scales as small as a few kilometers to tens of kilometers with repeat orbits on order of a day (e.g., Dickey, 1991). However, the sampling of the subsurface ocean on horizontal scales of hundreds of meters is presently limited to ship-based operations (e.g., tow-yo's). Extended sampling of longer than a few weeks is generally prohibitive because of shiptime costs (biweekly to monthly at best). For this reason, development and utilization of various platforms including autonomous underwater vehicles (AUV's) is highly desirable (Figs. 2, 3, and 4).

It has been suggested that only a limited number of comprehensive island or coastally based time series sites can be accommodated by the JGOFS program. Nonetheless, some of the most important locations reside in remotely located and environmentally hostile regions. In order to sample at such sites, it will be imperative to utilize automated sampling platforms including moorings, drifters, and AUV's.

One of the advantages of automated sampling is that data collected from such systems, in principle, can be transmitted in near real-time to shore-based laboratories around the world. The Argos satellite communication system (developed in the mid-1970's, instruments flown on NOAA weather satellites) is presently used by programs such as the Tropical Ocean Global Atmosphere (TOGA) program to distribute meteorological and physical data in near real-time (e.g., McPhaden, 1988). The near real-time capability is useful for continuous monitoring, planning sampling strategy, and for insuring data retrieval in the event of instrumentation loss or major malfunction in data recording. Near real-time communications

systems will be discussed in more detail later. The next sections will discuss the present status of and some potential future directions for automated systems

### **Examples of In Situ Automated Systems and Collected Data**

Development of autonomous sensors and systems requires special consideration of constraints such as sampling rate, power consumption, data storage, and biofouling. These constraints are common to both moored (fixed depth or profiling systems) and drifting modes; thus, the same sensors can usually be used for either application without major modification. Some of the variables which can now be measured autonomously in situ include: temperature, conductivity, currents, stimulated and natural (683 nm upwelling radiance) fluorescence, photosynthetic available radiation (PAR), beam transmission (660 nm), dissolved oxygen, pH, and downwelling and upwelling radiances (several wavelengths available, some matching SeaWiFS wavelengths). Other variables (shape, size, and concentration of living or detrital particles) are accessible by cameras (e.g., Asper, 1987; Gardner and Walsh, 1990; Walsh, 1990). Data are typically recorded every few minutes to every hour.

Acoustical systems are useful for current measurements and for determining distributions of organisms (e.g., zooplankton) larger in scale than phytoplankton (e.g., Haury and Pieper, 1987; Flagg and Smith, 1989; Plueddemann and Pinkel, 1989; Pieper et al., 1990) and can be used to provide important complementary spatial and time series data sets for ecological studies. Some variables cannot be determined in situ by analog devices, but coarse time series can still be obtained using samplers, such as sediment traps and water bottle samplers. Several successful experiments have now been done using moored and drifting bio-optical, physical, and geochemical sensors in the open and coastal ocean (e.g., Dickey, 1991).

### **Moorings**

Collection of moored bio-optical data began in coastal waters in the late seventies (e.g., Whitley and Wirick, 1983, 1986), but the use of moorings for this purpose in the open ocean has only recently begun (e.g., Dickey, 1991; note insert in Fig. 5). Nonetheless, data have been collected from moorings in several regions of the world ocean (see world map of Fig. 5 and summary in Table 1). Some of the moored sensors include: thermistors, conductivity sensors, vector measuring current meters, strobe fluorometers, natural fluorometers (683 nm upwelling radiance), photosynthetic available radiation (PAR) sensors, beam transmissometers (660nm), dissolved oxygen sensors, spectral downwelling irradiance sensors (410, 441, 488, 520 and 560 nm), and spectral upwelling radiance sensors for the same wavelengths (e.g., for Biowatt experiment in Sargasso Sea: Dickey et al., 1991; Smith et al., 1991; Dickey et al., 1992a; Marra et al., 1992). Data are typically recorded every few minutes to every hour. It is possible to do spectral analysis of bio-optical and biogeochemical data as well as physical data. The

processes contributing to variability shown in resulting spectra include diel cycles of phytoplankton, tides, inertial currents generated by passing weather systems and wind events, and internal gravity waves. For illustration, time series obtained from a multi-variable moored system (MVMS; see inset of Fig. 8) located at 10m depth south of Iceland (59N 21W) are shown in Fig. 6 (Dickey, 1991; Stramska and Dickey, 1992b; Dickey et al., 1992b). The work was done as part of the Office of Naval Research (ONR) sponsored Marine Light in the Mixed Layer (MLML) experiment (1989 and 1991), and the site was at the northern extreme of the JGOFS North Atlantic Bloom Experiment (NABE) conducted in the spring of 1989. During 1991, MVMS data were collected each minute for about two months (total of eight depths in the upper 250 m) and illustrate high variability in physical and bio-optical parameters. Advection associated with mesoscale current features and semi-diurnal tides are observed. Diurnal signals are seen at 10m in PAR, beam attenuation coefficient, stimulated fluorescence and derived primary production (not shown, see Dickey, 1991) based on upwelled radiance at 683 nm (Kiefer et al., 1989). The phases of these signals suggest that photoinhibition of the phytoplankton may be occurring (indicated by depressed fluorescence during mid-day; Stramska and Dickey, 1992b). Short time scale fluctuations associated with clouds are also apparent in the PAR time series. A major spring bloom event is evident after JD 140 when stratification begins abruptly. The 1991 MLML experiment was done at the Iceland site and included MVMS's as well as other moored optical (bio-optical moored systems [BOMS], Smith et al., 1991) and bioluminescence sensors (Case, personal communication), a moored Acoustic Doppler Current Profiler (ADCP; Plueddemann and Weller, personal communication), and temperature sensors.

Mooring data sets can presently be used to obtain high resolution time series of the following derived or modeled quantities: current shears, stratification, mixed layer depth, mixing time scales, particle concentrations, pigment biomass, depth integrated pigment biomass, primary production, "new" production (Dugdale and Goering, 1967), the vertical flux of particulate carbon, depth integrated primary production, oxygen respiration and utilization, and the flux of dissolved oxygen across the air-sea interface. Application of models to mooring data strongly suggests that short-lived episodic bloom events must be sampled for proper determinations of upper ocean carbon flux (e.g., Dickey, 1991; U.S. JGOFS Planning Report 14, 1992). It is likely that the magnitude and timing of seasonal and interannual variations may be impacted by a few intense events. Any detailed modeling of biogeochemical fluxes will require information on short as well as longer time scales.

There have also been coarse time series measurements using sediment traps (e.g., Honjo et al., 1990) and water bottle samplers (e.g., Abbott et al., 1990). In addition, ocean bottom sampling tripods (e.g., Berelson and Hammond, 1986) have been used for time series measurements.

## Drifters

The motivation for the use of drifters is to track water parcels to determine Lagrangian currents and to ascertain associated variability in bio-optical and biogeochemical parameters. Drogues are sometimes designed to track currents at a specific depth. Ideally, there is no slippage between the drifter or drogue and the water, so that in principle a given water parcel is followed (e.g., Niiler et al., 1988). This is a desirable situation for biogeochemical and bio-optical studies which are concerned with changes occurring within a specific water mass. Bio-optical and biogeochemical measurements from drifters have been attempted by only a few investigators (e.g., see Wilkerson and Dugdale, 1987). As one example, the Arctic Environmental Drifting Buoy (AEDB) was designed to obtain multi-disciplinary data in remote regions of the Arctic (Honjo et al., 1990). The buoy was equipped with thermistors, conductivity sensors, an ADCP, an electromagnetic current meter, two strobe fluorometers, a beam transmissometer, and a sequential sediment trap. The data obtained from these instruments and the position of the buoy were logged internally and transmitted via satellite using Argos transmitters during a drift of 3900 km in 255 days (Honjo et al., 1990, Fig. 5).

As part of the Coastal Transition Zone (CTZ) Experiment, Abbott et al. (1990) deployed a Lagrangian drifter (TriStar-II) with a tethered instrument package consisting of a spectroradiometer, a strobe fluorometer, a thermistor, and a beam transmissometer. In addition, an automated water sampler was located below the drogue at 17.5m and water was collected at 6h intervals for phytoplankton and nutrient analysis. Finally, a thermistor chain was placed beneath the water sampler for temperature measurements at depth. The drifter appeared to have followed a cold filament directed generally offshore. The drifter record is 8 days long and several interesting physical and bio-optical observations resulted. For example, the time series of temperature (Fig. 7) indicates that the water tracked by the drifter generally warmed (probably due to a combination of surface heating and advection), had a modest diurnal heating cycle, and occasionally changed in temperature abruptly (seen as steps) apparently because of encounters with frontal or water interleaving regions. The time series of downwelling light at 520 nm (Fig. 7) shows an expected diurnal cycle, with some modulation by clouds (also observed elsewhere by Dickey et al., 1991; Stramska and Dickey, 1992a; 1992b). Both the beam attenuation coefficient and stimulated fluorescence time series show diel rhythms and generally decrease in time (Fig. 7). It is likely that the beam attenuation diel rhythm is related to daytime particle (phytoplankton) production and nighttime grazing by zooplankton (e.g., Siegel et al., 1989; Hamilton et al., 1990; Gardner et al., 1990; Cullen et al., 1991; Stramska and Dickey, 1992b), however effects of variations in cell refractive index and size may be important as well (e.g., Ackleson et al., 1990). The diel rhythm in fluorescence is probably related to these same effects, but is modified by physiological modification of the phytoplankton which may either photoadapt to optimize growth, be photoinhibited resulting in a lower productivity, or have intrinsic diel rhythms (Kiefer, 1973). Other investigators are also planning large scale drifter studies utilizing bio-

optical sensors (Abbott, 1992; McLean et al., 1992; Abbott, Lewis, Hitchcock, and Olson, personal communications).

Another approach is to utilize an autonomous profiler equipped with bio-optical and physical sensors. The profiler, which ascends and descends by programmed buoyancy changes, can be either moored (e.g., Dickey and Van Leer, 1984) or used in drifter mode (Dickey, 1988; Marra et al., 1990; also under ice: Van Leer and Villanueva, 1986). The profiler (e.g., multi-variable profiler, MVP: see Dickey, 1988) can carry current meters, temperature and conductivity sensors, a transmissometer, a fluorometer, and a PAR sensor. Data have been transmitted via radio back to shore and ships for real-time data acquisition. This method frees ships for other concurrent sampling.

The isopycnal float (density following) fluorometer (IFF) developed by Hitchcock et al. (1989) includes a fluorometer, a pressure transducer, and a thermistor to measure subsurface water parcel motions (e.g., including upwelling and downwelling velocities) and simultaneous changes in chlorophyll a fluorescence in three dimensions. Temperature and pressure data are stored every 15 min and fluorescence data are stored every 30 m. Data collected over 4 hour intervals are transmitted via an acoustic link.

One of the principal attractions of drifters and floats, which are equipped with physical and bio-optical sensors, is that broad geographical regions can be sampled (representiveness is complicated by flow convergences etc.). On the other hand, the statistical interpretation of such data is quite complicated, since the measured variability results from variations in both space and time. Further, drifters' actual trajectories cannot be strictly interpreted as following water parcels' trajectories. In the future, some drifters will be designed to be recovered (some losses will be inevitable) while others will be considered expendable. Thus, for this approach to be viable for general usage, satellite telemetry of data and production of large numbers of sensors of moderate cost will be required.

## **Future Sensors and Systems**

### **Sensors**

Although much progress has been made in our capability to sample the marine ecosystem, its biogeochemistry, and its bio-optics, there remain several obvious high temporal resolution measurements which need to be included in future systems. For example, the further advancement of bio-optical measurements will require a variety of sensors which measure a more comprehensive set of optical variables so that inherent (those independent of a natural light source) and apparent (those dependent on a natural light source) optical properties may be related. Devices which are needed to better characterize the inherent optical properties are spectral absorption and scattering meters (e.g., Carder et al., 1988; Zaneveld and Bricaud, personal communication). The pump and probe fluorom-

eter of Falkowski et al. (1991) shows promise for primary productivity measurements. Applications of present instruments can be extended as well. For example, by modifying the emission/reception characteristics of a strobe fluorometer, it is possible to do measurements of fluorescence of specific pigments. This has been done by Iturriaga et al. (1990) for cyanobacteria. Finally, the use of fiber optics to bring light signals from depth to the surface for signal processing and data analysis appears to be a viable option for several physical and bio-optical applications (e.g., Cowles et al., 1990). Efforts are also underway to develop expendable instrumentation using fiber optics (e.g., Weidemann and Hollman, 1992). The measurement of apparent optical properties such as downwelling irradiance and upwelling radiance using spectral radiometers has progressed during the past decade. It will be most important for new in situ radiometers to be able to measure with higher spectral resolution (few nanometers) across the visible (and into the ultraviolet region) in order to link in situ data with advanced satellite (and aircraft) observations (multiplicity of wavelengths) and for spectral bio-optical models of primary production and species identification (e.g., Bidigare et al., 1987; Morel, 1991; Bidigare et al., 1992).

The development of fast response in situ autonomous chemical sensors for deployment from CTD and autonomous packages has begun with dissolved oxygen and pH sensors, but comparable sensors for total carbon dioxide and other specific ions (e.g. nutrients) are still under development for moorings and drifters (see ABOOS Symposium abstracts). However, development of chemical analyzers (involving reagents and active transportation of the fluids to detector) is relatively advanced (e.g., Johnson et al., 1992; Jannasch and Johnson, 1992). Acoustical systems are useful for current measurements and for determining distributions of organisms (e.g., zooplankton) larger in scale than phytoplankton (e.g., Haury and Pieper, 1987; Pieper et al., 1990) and can be used to provide important complementary spatial and time series data sets for ecological studies.

### **Autonomous Underwater Vehicles (AUV's)**

Exploration of the subsurface ocean has been done for the most part using submersibles or remotely operated vehicles, and thus required human intervention. These methods are costly and require considerable manpower. Thus, there is renewed interest in the development of autonomous underwater vehicles (AUV's) which could be used for regional and global sampling as well as exploratory operations. AUV's can be thought of as "robotic submarines." A generic AUV may be defined to be a free-swimming, untethered vehicle with its own power supply, propulsion unit, computer intelligence systems for decision making and navigation, communication links and telemetry, system and scientific sensors, and discrete water samplers.

Interestingly, several institutions have been involved in AUV development over the course of the past 30 years (see review by Blidberg, 1991). Development of prototype AUV's is currently underway at several institutions in the U.S. These include: the University of New Hampshire (Experimental Autonomous Vehicle

[EAVE], Blidberg, 1991), Florida Atlantic University (Ocean Voyager, Dunn, 1991), Woods Hole Oceanographic Institution (Autonomous Benthic Explorer [ABE], Yoerger et al., 1991), the Draper Laboratory [DARPA/Navy Test-Bed UUV], Pappas et al., 1991), and the Naval Postgraduate School (NPS AUV, Brutzman and Compton, 1991). Besides efforts in the U.S., a major thrust is being made by the British as they are developing the Autosub (Woods, 1991a,b; McCartney and Collar, 1991) with specific application for climate-related hydrographic work which will continue beyond the World Ocean Circulation Experiment (WOCE) and the British Biogeochemical Ocean Flux Study (BOFS). The French too have been leaders in the development of AUV's (see Blidberg, 1991). The current enthusiasm for AUV's is spurred in part by technological advances in miniaturized computers and artificial intelligence. In addition, a broader suite of oceanographic sensors and water samplers is now available. Several of the necessary electronics, computer control, and scientific sensor capabilities are being utilized for moored and drifter instrumentation used for bio-optical and biogeochemical as well as physical observations as described earlier.

A workshop on AUV's, sponsored by the National Science Foundation, recently brought together ocean engineers presently working on AUV technology and scientists interested in problems which may benefit from utilization of AUV's (see Blidberg and Sedor, 1991). Some of the important conclusions relevant to the JGOFS and C&GC program objectives included:

1. AUV's can benefit the oceanographic community by enabling unique sampling which cannot be accomplished with other existing platforms and by providing cost-effective and expanded oceanic observational capabilities.
2. Technological advances over the past decade have made the utilization of AUV's a potentially feasible option for many physical, bio-optical, and geochemical research efforts.
3. AUV's are envisioned as being capable of providing data on horizontal and vertical scales which complement sampling from satellite, mooring, and ship platforms, but will not replace these sampling modes. They are particularly attractive platforms for 4-dimensional (space plus time) mapping applications (especially where horizontal gradients are intense). Initial studies, which do not require endurance beyond a few days, could include mapping in the vicinity of time series sites (preferably in vicinity of moorings) and coastal outfalls. The JGOFS Hawaii and Bermuda time series sites would be excellent candidates for such preliminary efforts.
4. Some of the special studies which could be done with an AUV include: active object following (e.g., marine snow, plankton, and nekton), plume signature (based on gradients) tracking, finding sources of Antarctic bottom water, and sediment trap monitoring. Also, AUV's could be used on a "stand-by" basis (cued by near real-time mooring and satellite data) for rapid response to explore important phenomena such as the role of major oceanic storms in promoting nutrient flux to the euphotic zone and open ocean blooms of *Trichodesmium*.
5. Major AUV development areas which need to be addressed include reliability (greater than 10,000 hours), endurance (greater than 1,000 km), and longevity

of missions (from present capability of a few days to at least 30 days).

AUV technology needs to be considered in the planning of future regional and global studies such as JGOFS and NOAA's global ocean observing system. Their use at time series sites, in process studies, and for large scale observations could facilitate the accomplishment of many of the goals of JGOFS and C&GC as well as many other programs in the future. AUV development is progressing (see ABOOS Symposium abstracts), but it must be emphasized that utilization for JGOFS and C&GC will depend on support and success of engineering efforts. It will be important to develop cooperative efforts with other countries which are active in the development of AUV's. There appear to be no major technological barriers to successful development. Further, it is likely that most sensors which are being, or will be, used on moored and drifter systems can be used on AUV's. AUV data telemetry will probably rely heavily on acoustical and satellite methods (see Telemetry section).

### **Data Management Issues**

The collection of interdisciplinary data from automated systems at relatively high sampling rates has become possible only within the past few years (e.g., review by Dickey, 1991). Thus, problems concerning the management of the resulting data, while considerably less severe than those of satellite oceanographers, are of concern for our community. On the other hand, they are similar to, though somewhat more demanding than, those of physical oceanographers as time series of many more variables are being collected.

The following discussion concerns a hypothetical estimate of the future annual volume of data which may be collected using automated sampling systems for programs such as JGOFS or NOAA's global ocean observing system. As such, nominal values of parameters are based on past sampling regimes and no adjustments for specific sensor failures, etc. were made (Tables 1 and 2). Many of the reports are very recent and detailed information remains rather incomplete. These tables are also useful for illustrating the remarkably fast growth rate of this approach to oceanography (also see inset in Fig. 5). The projected data amounts (Table 3) are only hypothetical, but serve to suggest potential data management needs. The amount of data ( $A$ , in bytes) obtained from a particular instrument at a given depth and for a specific period is given by

$$A = d \times n \times r \times T$$

where

$d$  = no. of bytes of data/no. of variables/no. of records

$n$  = no. of variables

$r$  = no. of records/unit of time

$T$  = duration of deployment

As an example, data (10 variables) were collected from one MVMS in the Sargasso Sea (Biowatt) in 1989 (Dickey et al., 1991, 1992a) at a sampling rate of once per 4 minutes for approximately 9 months ( $3.89 \times 10^5$  minutes) in 1987. Using the formula above,

$$A = (4 \text{ bytes/var/rec}) * (10 \text{ var}) * (1 \text{ rec}/4 \text{ min}) * (3.89 \times 10^5 \text{ min})$$

$$A = 3.89 \text{ Megabytes (Mbytes) per MVMS}$$

where var is the number of variables and rec is the number of records. For the Biowatt Sargasso Sea experiment, eight MVMS and two to three BOMS were used giving a potential of about 34 Mbytes of data. Again, similar measurements were done south of Iceland (MLML) for about 2 months in 1989 (Dickey et al., 1992b, Stramska and Dickey, 1992b) and for about 4 months in 1991, but with a few more variables and at a sampling rate of once per minute. More recently, we have done MVMS measurements (total of 4) off the coast of California (NOAA's Sea Grant program, Dickey and Manov, 1991) at a rate of once per minute for 2 months, and presently data are being collected in the equatorial Pacific (NSF: JGOFS/NOAA: C&GC program, Dickey, in progress) using 4 MVMS at a rate of once per 3.75 min (for the sake of compatibility with other instruments sampling rate). The volume of MVMS data thus far collected amounts to over 150 Mbytes. These data sets are processed on an advanced VAX II computer. Several steps are required in the processing. These include: conversion from voltages to engineering units (including calibration), error checking, statistical analysis, and graphical products (e.g., time series plots, contour maps, etc.). Various filtering schemes are applied depending on the frequency domains of interest.

Several mooring and drifter studies were used to compile data amounts for work done within the past 15 years, however most of the data have been collected within the past 5 years (inset of Fig. 5). Several studies are summarized in Tables 1 and 2. Again, some very recent studies were described at the ABOOS Symposium in the form of abstracts. As an exercise, we have made the following hypothetical projections. We suppose that on an annual basis, there may be as many as 1) 30 moorings collecting data (~24 variables) at 4 depths at a rate of once per minute at various sites of the world ocean, 2) 200 drifters collecting data (~22 variables) at 2 depths at a rate of once per minute [roughly equivalent to 8000 drifters sampling 10 variables at 1 depth: an alternative approach], and 3) 10 AUV's collecting data (~22 variables) at a rate of once per minute. Using this information and the above equation, we estimate that the annual volume of data collected from automated in situ systems would be approximately 6.2 Gbytes per year.

Many available work stations are suitable for most of the required computational activities. Software packages such as the Interactive Display Language (IDL) provide large libraries of subroutines that run on UNIX operating systems. The software also supports window and graphic environments. Workstations can also be used to produce color maps, 3-D images, and vertical profiles of interdiscipli-

nary data. The volume and complexity of these multi-variable data sets require new and innovative methods of data reduction, display, and integration with complementary data (e.g., meteorological and historical data). In terms of long-term data management, raw and processed data sets need to be backed up on storage media such as tapes or preferably optical disks. Access to data can be provided through a variety of computer networks.

### **Near Real-time Telemetry**

One of the implicit goals of global programs such as JGOFS and C&GC is the development of observing systems which, in large numbers, would collectively facilitate the long-term collection of interdisciplinary oceanographic data in near real-time in analogy to international atmospheric programs such as the World Weather Watch (e.g., Baker, 1991). These future data will serve several purposes. They will be used to give descriptions of the state of the oceans, for development of parameterizations for models, and to provide initial conditions for short-term as well as climatic-scale forecasts. For many satellite applications, near real-time telemetry is already a natural part of the process and will continue to be (e.g., Evans, 1992). However, the telemetry of in situ data is still a developing area, though the basic technology is available (e.g., Frye et al., 1991; Brooks and Briscoe, 1991; Walker, 1991). It should be noted that the telemetry of in situ data from platforms such as moorings, drifters, and AUV's is further motivated by the need for experimental design and sampling strategy, for diagnosis of instrumentation problems, for modifying sampling rates, and importantly by the need to insure against the loss of data because of damage to or loss of the platforms.

True real-time (no delay) data transmission of interdisciplinary data from sampling platforms has generally been confined to nearshore deployments thus far. Booth et al. (1987) used a direct electrical conducting cable connection to transmit data collected near Scripps Institution of Oceanography. Radio telemetry of data collected from near surface instruments has been used off the coasts of Long Island (Whitledge and Wirick, 1983), Peru (Dickey and Van Leer, 1984), Monterey, California (Chavez et al., 1991, 1992), and Los Angeles (work recently completed by Dickey et al. and Walker and Douglass, 1992). The experimental mooring and the telemetry system used for the Los Angeles study are illustrated in Fig. 8 with resulting near real-time data collected from the 10m MVMS being shown in Fig. 9. Both telemetered (crosses) and stored (dots) data are shown for two days of a 40-day time series. For open ocean problems, this methodology is too geographically restrictive.

An interesting approach to the data telemetry problem has been described by Brooks and Briscoe (1991). They reported on tests of high-frequency ionospheric radio propagation systems which do not involve satellites. This methodology has become more practical with advances in antennas, receivers, and digital data processing. These systems are relatively economical in cost and capable of passing data at moderate rates (~1-10 bits/sec) averaged over several days. Higher data

rates (possibly up to ~100 bits/sec) may be possible under optimal conditions. One disadvantage is that it may be necessary to store data for days to weeks prior to transfer because of the need to have adequate propagation path characteristics, thus impairing the more truly near real-time capability. However, the technology is readily available and two-way exchanges are possible. The coverage is essentially global, but intermittent and dependent on sunspot activity, interference, and skip zones. The ocean hardware necessary for this approach will be more suitable for reusable ocean buoys rather than small expendables.

The two primary types of satellite telemetry systems for obtaining near real-time (delay of few hours to one-half day in general) are polar-orbiting systems such as the NOAA TIROS satellites with Argos data collection systems and the geosynchronous satellite systems such as the Geostationary Operational Environmental Satellites (GOES), Meteosat, and TDRSS. Several systems are reviewed by Briscoe and Frye (1987), Brooks and Briscoe (1991), and Frye et al. (1991).

Briefly, the polar-orbiting system has the advantage of being able to track large numbers of drifters, but has only limited capability of transferring large amounts of data. For example, Argos can be used to transmit only 32 bytes at 1-minute intervals with the satellite being generally in view for only 10 minutes ten times per day (~3 Kbytes/day) with other factors reducing the data throughput to ~0.1 bit/sec. The Argos satellite communication system is presently used by programs such as the Tropical Ocean Global Atmosphere (TOGA) program to distribute meteorological and physical data in near real-time (e.g., McPhaden, 1988). As indicated earlier, there is a great need to extend near real-time capability to the open ocean. This is true for moorings along with drifters and AUV's. The transmission requirements are relatively severe and beyond the capacity of Argos. For example, if MVMS sampling were done at 4 min intervals for 4 depths, about 650 Kbytes of data would be generated each day. It should be noted that Argos collects less than 3 Kbytes per day and does not provide a command link. The Argos system could handle only a minimal subset of these data. Geosynchronous satellite systems enable transmission rates of 100 bit/sec, but data transmissions are typically limited to once per 1-3 hours giving average data rates of 1 bit/sec. In addition, these systems require ground stations with relatively high power and/or directional antennas (e.g., Brooks and Briscoe, 1991).

Other existing systems include the geostationary Applications Technology Satellite (ATS) which is not expected to be in operation in the future, the commercial INMARSAT Standard C system which requires high power levels and relatively complex antennas (e.g., Brooks and Briscoe, 1991), and the Tracking and Data Relay Satellite System (TDRSS). The latter system was developed under the direction of the National Aeronautics and Space Administration (NASA) at the Goddard Space Flight Center (GSFC) and placed into service during the mid-1980's. The TDRSS provides nearly continuous communications between a ground station located at White Sands, New Mexico and low earth orbiting (LEO) satellites. The system consists of three geostationary (GEO) satellites plus the White Sands Ground Station. One satellite is located over the Atlantic at a longitude which

provides line-of-sight with the ground station at an elevation angle of 5 degrees. The second satellite is located at an equivalent location over the Pacific. The third satellite is an on-orbit spare located over the central continental U.S. With this geometry, the system provides nearly continuous line-of-site communication with LEO satellites with the exception of a 20 degree swath centered 180° from the ground station. This provides a single point for two-way communications without the need for multiple ground stations around the globe. The TDRSS provides three types of communication links: 1) the KSA - single access Ka-band supports up to 300 Mbits/s (Mb/s), 2) the SSA - single access S-band supports up to 10 Mb/s, and 3) MA - multiple access S-band, supports up to 50 Kbits/s (Kb/s). The single access links support one satellite user at a time. The multiple access system can receive telemetered data from up to 20 simultaneous users. This is accomplished by electronically forming 20 separate electronic beams. Each beam has a diameter of 3000 to 4000 miles projected on the surface so point requirements are very coarse. The formed beam permits a 30-fold increase in achievable data rate for a given platform transmitter power. For example, a 4 watt transmitter can support 1 Kb/sec (125 bytes/sec) or 7500 bytes/min. TDRSS has not been utilized for oceanographic data telemetry as yet; however with the development of moderately priced transmitters, it holds great promise.

An alternative system planned by Motorola Corporation is summarized by Brooks and Briscoe (1991). The satellite-based global cellular telephone system, called Iridium, would involve 77 low-orbit satellites which would require only small antennas with low power levels for ground stations (e.g., moorings and drifters). The system data rate capacity is estimated to be ~1000 bits/sec.

Another conceptual satellite system, the global environmental data distribution system (GEDDS), would require a single small satellite operating in a low polar orbit (Walker, 1991). The system would include a command link which would allow investigators to control sampling rates and recalibrate instruments on a daily basis from their laboratories. As with Iridium, the low satellite altitude would permit small antennas and low power levels to be used on the platforms. GEDDS, with a single satellite, would be relatively inexpensive. It would consist of a transponder/processor package mounted on the environmental sensor platform and a satellite package consisting of collection and relay transponders and antennas plus a processor. The system would be controlled from a small ground-based control center which could be located almost anywhere. The satellite would make 14 nominal north-south revolutions per day, interrogating and reading data as it passes over. The GEDDS could collect and distribute over 340 Mbytes of data per day and support over 4000 platforms. Platforms in the temperate zones could be accessed at least three times per day and could transfer from 8 to 800 Kbytes during each access. Platforms in the polar regions not covered by geostationary satellites (e.g., GOES and INMARSAT) could be accessed up to 14 times per day giving a selectable daily throughput of 112 to 11,200 Kbytes. Based on an average of 3 accesses per day at 80 Kbytes per access, an average daily throughput of 240 Kbytes (1,920 Kbits) could be achieved. This corresponds to an approximately 20 bit/s average compared to 0.1 bit/second for Argos. GEDDS could accommodate

from 100 bits/second to 400 bits/s average throughput for selected platforms depending on their location and specific requirements. Finally, GEDDS would use conventional platform hardware and require minimal development. It could be used in conjunction with global positioning satellites (GPS) for location of moving platforms.

To this point, we have addressed the linkage of data from surface-based transmitters to shore either directly or via satellite. The problem of transferring data from subsurface instrumentation to surface transmitters has received increasing attention and is vital to relatively deep instrumentation (e.g., deep moored instruments, AUV's which may not come to the surface frequently, and deep drifters). A direct approach for moorings is to use conducting cable or fiber optical links from subsurface instruments to the surface buoy and transmitter. For relatively shallow instruments (~10-20 m), this approach has been satisfactory; however, for deeper instruments the probability of mechanical damage to the cable or fiber is quite high and the terminations are costly and labor-intensive. Several other subsurface data telemetry approaches have been described by Frye et al. (1991). These include electrical inductive and acoustical telemetry. The inductive method involves a modem and a toroid placed around the mooring cable for coupling of the signal without a direct electrical connection. The signals are detected and amplified by a receiver at the surface. Data rates of ~1,200 bits/s at low power have been reported. Acoustic signal transmission is attractive because of the excellent sound transmission characteristics of water and the available acoustic technology and signal processing capabilities. Complications do arise because of variability in water properties and ambient noise. However, data rates as great as 5,000 bits/s have been achieved with relatively low error rates (Frye et al., 1991).

To review, data communications systems typically used for oceanographic applications have telemetry data rates which are generally too limited for many interdisciplinary systems. However, considerable progress has been made in the areas of subsurface to surface and surface to shore data transmission. In the next few years, it should be possible to adequately transmit a high percentage of interdisciplinary data collected from moorings, drifters, and AUV's in support of programs such as JGOFS and NOAA's global ocean observing system.

## Summary

In summary, automated sampling from moorings, drifters, and AUV's are important for the JGOFS and NOAA programs as they may be used to:

1. Establish relationships between biogeochemical processes (particularly carbon transport from the euphotic layer) and physical forcing;
2. Intercompare several methods for the determination of primary production from moored instrumentation and sediment traps as well as radioisotope methods (e.g.,  $^{234}\text{Th}$ );

3. Make accurate vertical, horizontal, and temporal estimates of pigment biomass and phytoplankton productivity leading to fluxes of carbon;
4. Enhance understanding of relationships between primary production and export of carbon from the upper ocean and to model the flux of carbon through the upper ocean;
5. Maximize the accuracy of future regional and global satellite pigment biomass and phytoplankton productivity estimates.

Many of the present uncertainties in the estimation of carbon budgets are caused by 1) undersampling, both in time and space, 2) limitations in existing measurement techniques involving primary production and sediment trap methodologies (Jahnke, 1990), and 3) the lack of concurrent physical, bio-optical, and biogeochemical data. Observations from moorings, drifters, AUV's, ships, and satellites all have sampling advantages and disadvantages. It is anticipated that the well-planned utilization of these collective platforms will be most useful in reducing many of the present ambiguities and provide new insights into the complicated carbon cycle, thus facilitating the modeling and ultimate prediction of global climate change. Finally, applied coastal problems involving water quality issues and perturbations of the natural ecology can also benefit from the emerging technological capabilities described here.

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Table 1. Interdisciplinary Mooring Studies.

Study	Location	Experimental Period	D a y s	D e p t h s	Variables	N o. V a r.	Int. (min)	Data Amount	Reference
Long Island*	(1) Long Island Shelf (40N, 72W)	Aug.-Sept. 77	21	1	t,U,V,T,C,Fl	6	20	36Kbytes	Whitledge & Wirick (1983)
SEEP Pilot**	(1) Long Island Shelf (40N, 72W) Maryland Shelf (37N, 74W)	July 82	6	1	t,T,Fl,c,p	5	8	48Kbytes	Whitledge & Wirick (1986)
		Apr. 83	7	1					
SEEP***	(1) Long Island Shelf and Martha's Viny. (-40N, 71-72W) Maryland Shelf (37N, 74W)	Sept. 83-Mar. 84	330	5**	t,U,V,T,C,Fl,c	7	16 to 20 34 to 68	Roughly 3Mbytes	Walsh et al. (1988) Falkowski et al. (1988) Churchill et al. (1988) Flagg (1988) Medeiros & Wirick (1992)
		Apr.-Oct. 84	415	2-3	t,T,Fl,c (PAR, DO)				
		Feb. 88 - May 89							
Scripps Canyon*	(2) Scripps Canyon (33N 117W)	Apr.-May. 84 Nov. 85-Jun. 86	300	1	t,U,V,T,C,p,c,Fl, Ed( $\lambda$ ),Eu( $\lambda$ ),Lu( $\lambda$ )	40	5	14Mbytes	Booth et al. (1987)
Antarctica	(3) Antarctica (70S, 24E)	Dec. 85-Feb. 86	47	1	t,U,V,T,p,Fl	6	60	27Kbytes	Fukuchi et al. (1988)
Biowatt (MVMS)	(4) Sargasso Sea (34N, 70W)	Mar.-Nov. 87	265	8	t,U,V,T, C,PAR, c,Fl,DO	9	4	24Mbytes	Dickey et al. (1991)
Biowatt (BOMS)	(4) Sargasso Sea (34N, 70W)	Mar.-Nov., 87	265	2 or 3	t,Ed( $\lambda$ ),Lu( $\lambda$ ),T,p	13	4	10Mbytes	Smith et al. (1991)
MLML I (MVMS)	(5) South of Iceland (59N, 21W)	Apr.-Jun., 89	60	8	t,U,V,T, C,PAR, Lu(683),c,Fl,DO	10	1	31Mbytes	Dickey (1991) Dickey & Marra (in progress)
MLML II (MVMS)	(5) South of Iceland (59N, 21W)	May-Sept., 91	126	8	t,U,V,T, C,PAR, Lu(683),c,Fl,DO	10	1	65Mbytes	Dickey & Marra (in progress)
MLML II (BOMS)	(5) South of Iceland (59N, 21W)	May-Sept. 91	126	3	t,Ed( $\lambda$ ),Lu( $\lambda$ ), T,p,c,Fl	15	4	8Mbytes	Smith et al. (in progress)
Ocean Outfall I (MVMS)	(6) Los Angeles Coast (118N, 34N)	Jan.-Feb. 91	51	2	t,U,V,T, C,PAR, Lu(683),c,Fl,DO	10	1	10Mbytes	Dickey & Manov (1991)
					t,U,V,T, c,p	6			
Ocean Outfall II* (MVMS)	(6) Los Angeles Coast (118N, 34N)	Jan.-Feb. 92	40	2	t,U,V,T, C,PAR, Lu(683),c,Fl,DO	10	1	8Mbytes	Dickey et al. (in progress)
					t,U,V,T, c,p	6			
OASIS*	(7) Monterey Bay, CA (37N, 123W)	In progress	-	2	t,U,V,T,C,c,Fl Ed( $\lambda$ ),Lu( $\lambda$ )	17	15	-	Chavez et al. (1992, work in progress)
GCC/IGOFS (MVMS)	(8) Equat. Pacific (0, 140W)	Nov. 91-Apr. 92	180	4	t,U,V,T, C,PAR, Lu(683),c,Fl,DO	10	3.75	11Mbytes	Dickey et al.
GCC/IGOFS (MVMS)	(8) Equat. Pacific (0, 140W)	Apr. 92-Nov. 92	180	4	t,U,V,T, C,PAR, Lu(683),c,Fl,DO	10	3.75	11Mbytes	Dickey et al.

(Continued on next page)

Study	Location	Experimental Period	Days	Depths	Variables	No. Variables	Int. (min)	Data Amount	Reference
OPTISENS	(9) Norwegian Coast	1988-present	?	1	t, $\sigma$ (470,555,650)	4	?	?	Volent & Johnsen (1992)
Miscellaneous Fluorometer/Current meter Moorings	(10) Bering and Chukchi Seas (62-68°N) (11) Georgia Cont. Shelf (12) Gulf of Eilat in Red Sea	Unknown	?	?	Fluorescence Currents	4?	?	?	Wirick (1992)
Prototype Mar. Optical Buoy System*	(13) Hawaii (open ocean)	Planned	N/A	Near Sfc.	2 spectrographs: radiometric mea. with high spectral resolution & stray light rejection	?	?	?	Clark et al. (1992)
Red Tides****	(14) Osaka Bay (15) Lake Biwa	1988-1991 1990-present	?	(0-20m) (0-100m)	t, T, S, pH, DO, c, nuts., Chl	13	?	?	Kimoto et al. (1990) Kimoto (1992)
ADEOS Buoy*	(16) Tokyo Bay (17) Yamato Bank	Dec. 1991-present Planned	?	1 2	t, Chl, E <sub>d</sub> (λ), L <sub>u</sub> (λ) same as above	12 12	?	?	Matsumura et al. (1992)
REOS*	(18) Los Angeles reservoir*	1990-1992	600	1	t, Nat. Fluor., T, c PAR, DO, pH, Cond.	9	5 & 15	3Mbytes	White et al. (1991) Morrow et al. (1992)
Expendable Spect. Rad. (moor. tests)	(19) Bedford Basin	1992	?	1	t, L <sub>u</sub> (λ), sfc E <sub>d</sub> (490), SST	10	?	?	McLean et al. (1992)

\* Indicates telemetry was used.

\*\* Sensors were not necessarily co-located.

\*\*\* The SEEP project utilized up to 10 moorings. Sensors were placed at several depths, but were not necessarily co-located, therefore the estimates of data amounts are not computed in the same manner as sensor suite data. The reader is directed to the references for details concerning the actual experimental parameters.

\*\*\*\* Barge or mooring buoy used.

Table 1. Interdisciplinary mooring studies including locations, sampling periods, duration of sampling in days, number of depths of instruments, variables sampled, number of variables, sampling intervals (int. = 1/rate), data amounts in bytes, and references.

Study	Location	Experimental Period	Days	Depths	Variables	No. Variables	Int. (min)	Data Amount	Reference
(20) MVP*	(20) Sargasso Sea & Tongue of the Ocean	Spring 1985	10	10-300m	t, T, cond., currents, Fl, PAR	7	0.3 hourly profile	1.2Mbytes	Dickey (1988) Marra et al. (1990)
(21) IFF**	(21) Gulf Stream (37N, 73W)	Sept. 1986	4	Var.	t, T, Fl, p	4	1.5	61Kbytes	Hitchcock et al. (1989)
(22) CTZ	(22) Central Calif. Coast (38N, 125W)	Jun. 87	4	1	t, T, c, Fl, p E <sub>d</sub> (λ), L <sub>u</sub> (λ)	15	4	173Kbytes	Abbott et al. (1990)
(23) AEDB*	(23) Arctic (65-87N, 20E-30W)	Aug. 87-Apr. 88	255	2**	t, U, V, T, Fl, c, p	7	60	343Kbytes	Honjo et al. (1990)

\* Indicates telemetry was used.

\*\* The Isopycnal Float Fluorometer (IFF) system follows isopycnal surfaces and thus varies in water depth (~40-80m for this study).

Table 2. Interdisciplinary drifter/float studies with information as described in Table 1.

Study	Number	Days	Depths	Variables	No. Vars.	Int. (min)	Data Amount
Moorings	30	365	4	t,U,V,T,C,p,c,Fl, DO,pCO <sub>2</sub> ,nuts., PAR,E <sub>d</sub> (λ),L <sub>u</sub> (λ)	24	1	6Gbytes
Drifters (incl. Floats)	200	365	2	t,T,C,p,c,Fl,DO, pCO <sub>2</sub> ,nuts.,PAR, E <sub>d</sub> (λ),L <sub>u</sub> (λ)	22	1	18Gbytes
AUV's	10	365	Var. (1 unit)	t,T,C,p,c,Fl,DO, pCO <sub>2</sub> ,nuts.,PAR, E <sub>d</sub> (λ),L <sub>u</sub> (λ)	22	1	464Mbytes
<b>Total</b>	<b>225</b>	<b>365</b>					<b>25Gbytes</b>

Table 3. Hypothetical interdisciplinary mooring, drifter/float, and AUV studies which could be done over the world oceans with information as described in Table 1.

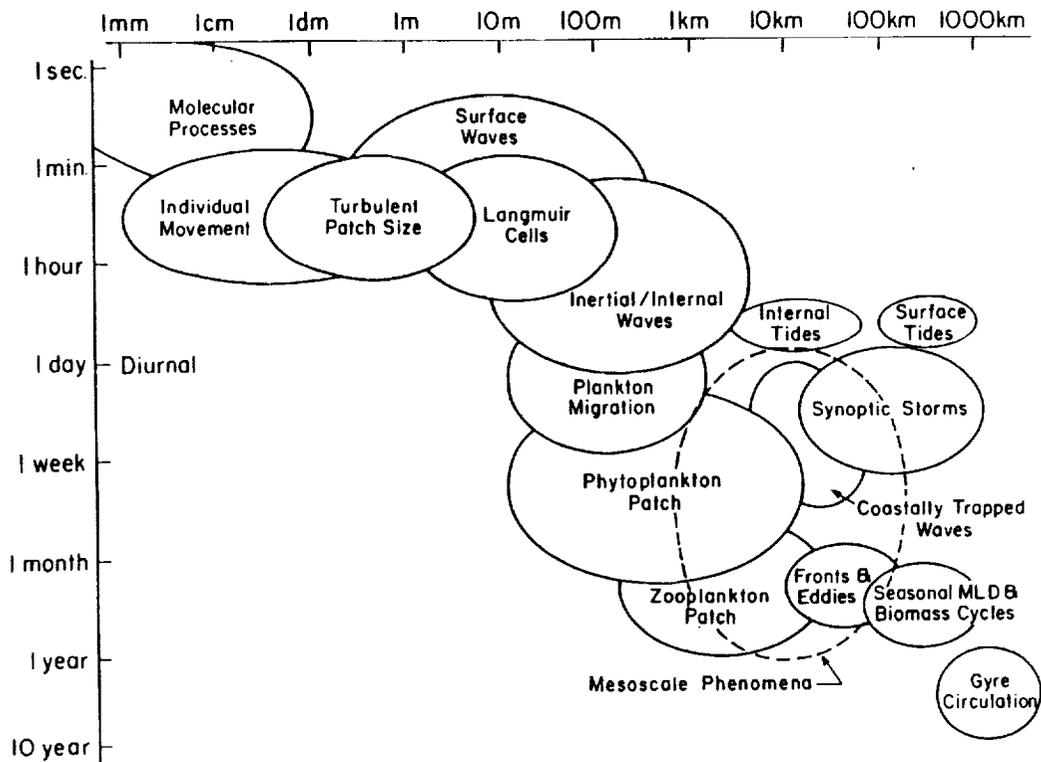


Figure 1. A schematic diagram illustrating the relevant time and space scales of several physical and biological processes important to the physics, biogeochemistry, and ecosystems of the upper ocean (after Dickey, 1991).

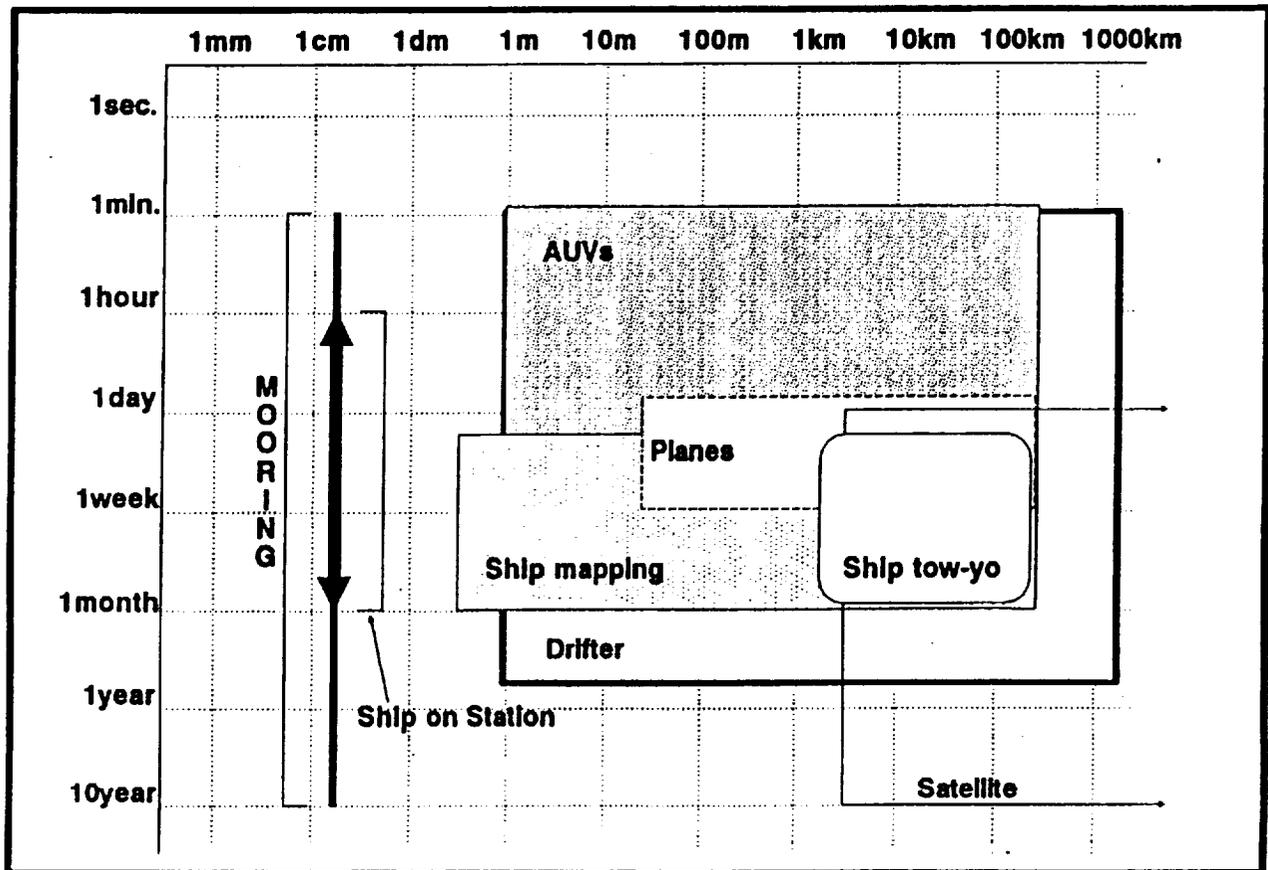


Figure 2. Temporal and horizontal spatial sampling coverage of several platforms (based on Dickey, 1991; after Bidigare et al., 1992).

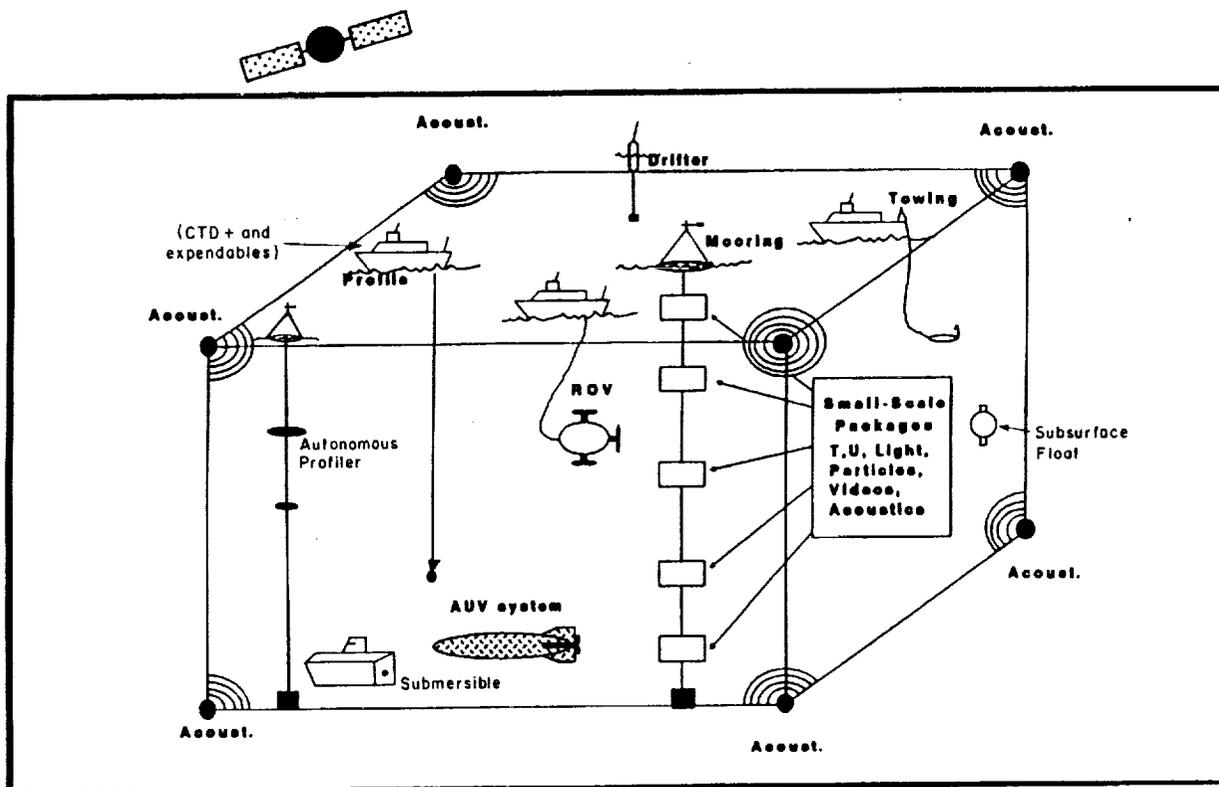


Figure 3. A conceptual illustration of a "nested" in situ biogeochemical-bio-optical-physical sampling configuration designed to sample processes with a broad range of temporal and spatial scales (after Dickey, 1991).

**DETERMINING BIO-OPTICAL PROPERTIES (x,y,z,t)**

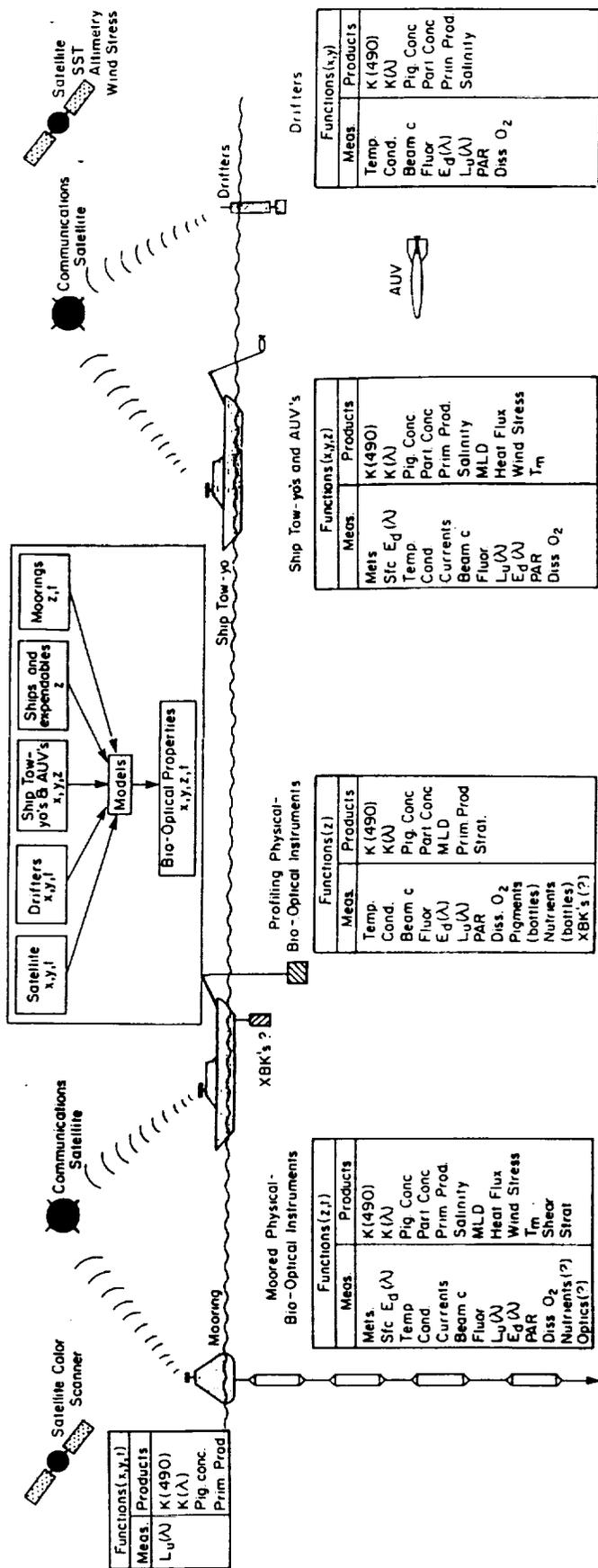


Figure 4. A schematic illustrating a methodology for determining the variability of bio-optical properties in space and time on a global basis using satellite as well as in situ data sets along with appropriate models. Applications could include determinations of the subsurface light field, primary production, particulate carbon fluxes, and the penetrative component of solar radiation (based on Dickey, 1991).

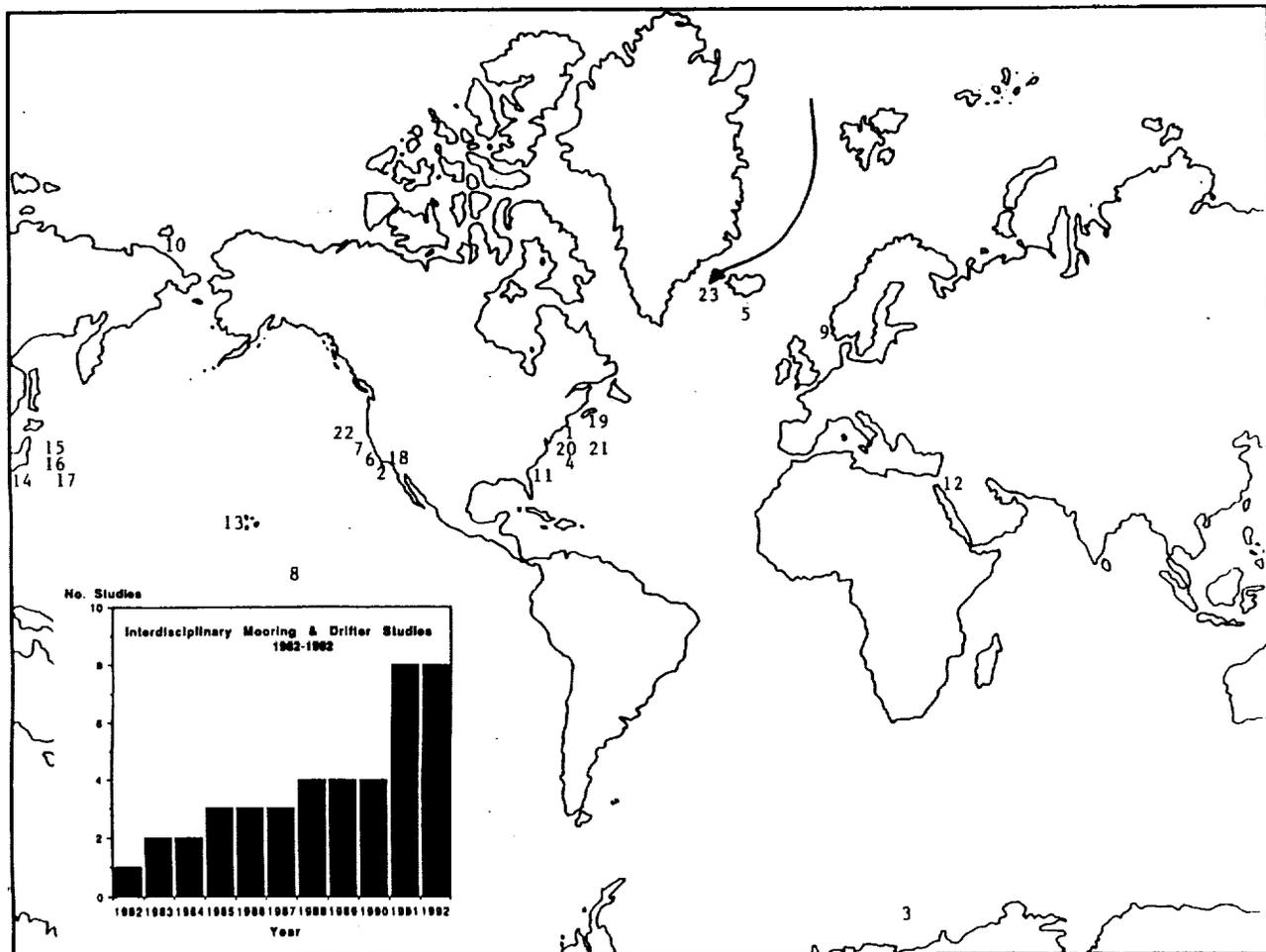


Figure 5. World map indicating sites of previous and present bio-optical/physical moorings (sites 1-19) and drifters (sites 20-23). The insert shows a time series of the approximate number of interdisciplinary mooring and drifter studies from 1982 to present. Details are given in Tables 1 and 2.

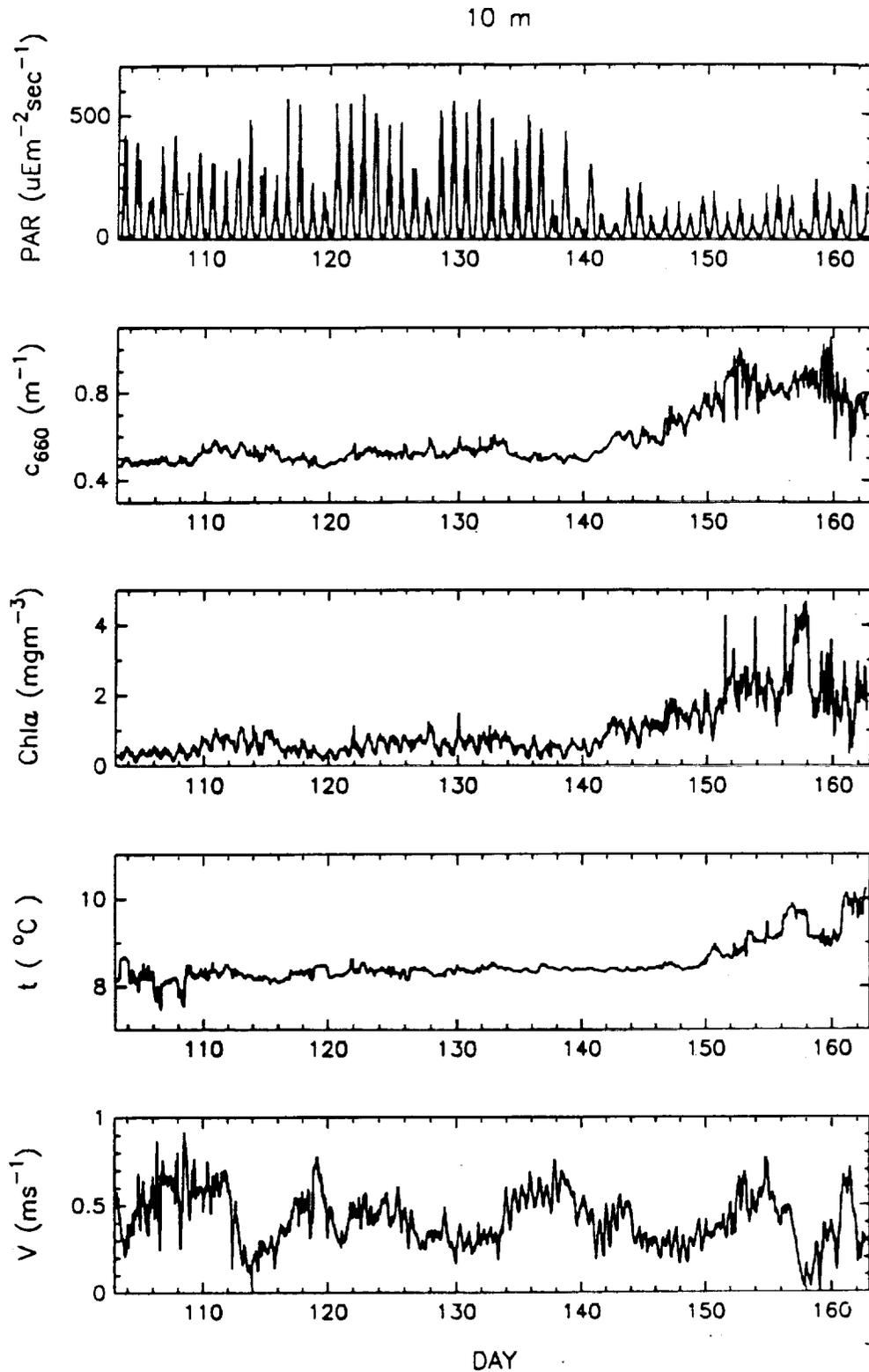


Figure 6. Time series of physical and bio-optical data taken from an MVMS located at 10m on a mooring south of Iceland (59N 21W) in April 1989. Time series include: photosynthetic available radiation or PAR ( $\mu\text{E m}^{-2} \text{s}^{-1}$ , beam attenuation coefficient at 660nm, stimulated chlorophyll fluorescence ( $\text{mg m}^{-3}$ ), temperature ( $^{\circ}\text{C}$ ), and current speed ( $\text{m s}^{-1}$ ). Sampling rate was once per minute. (Dickey et al., 1992b).

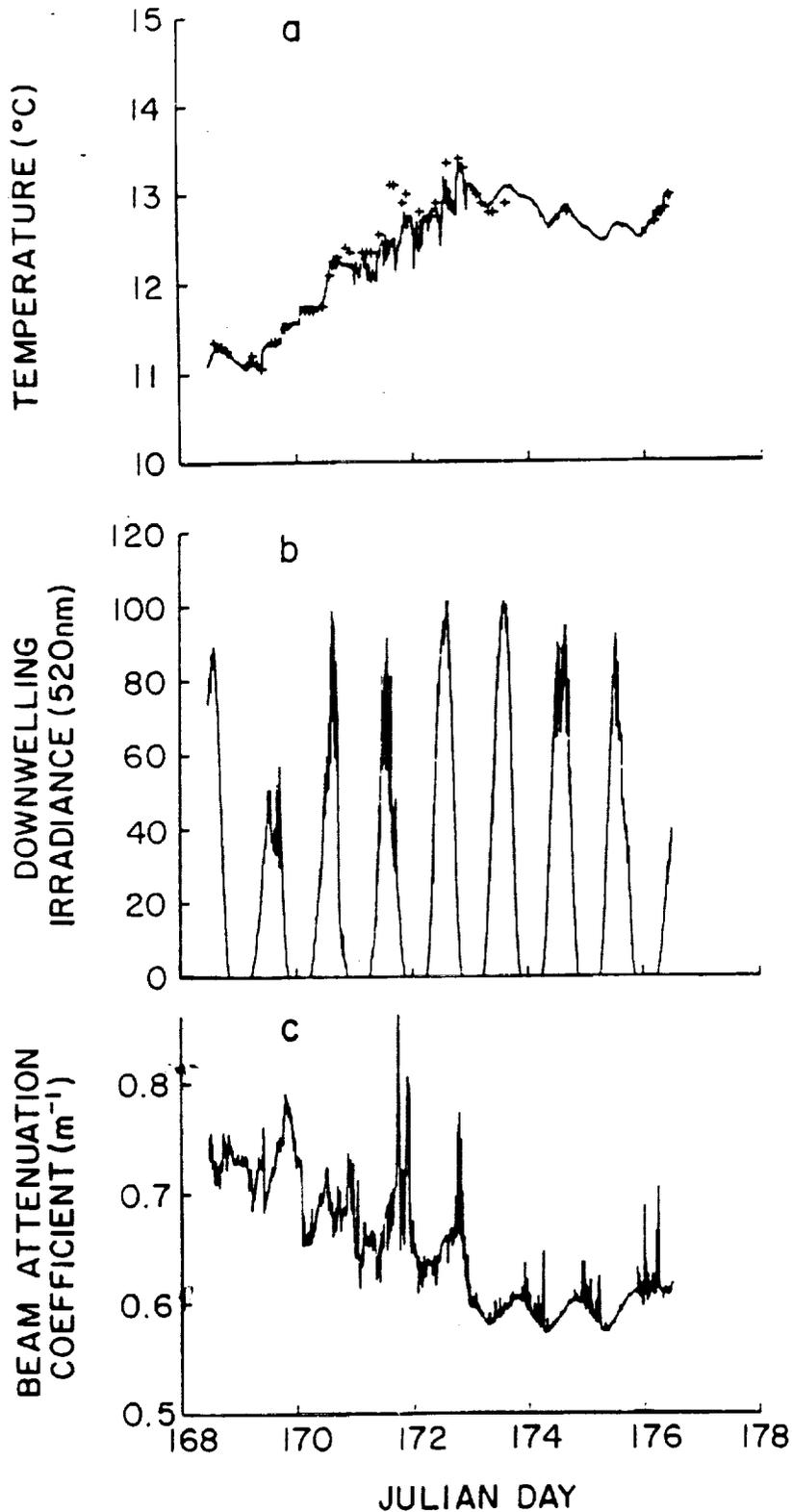
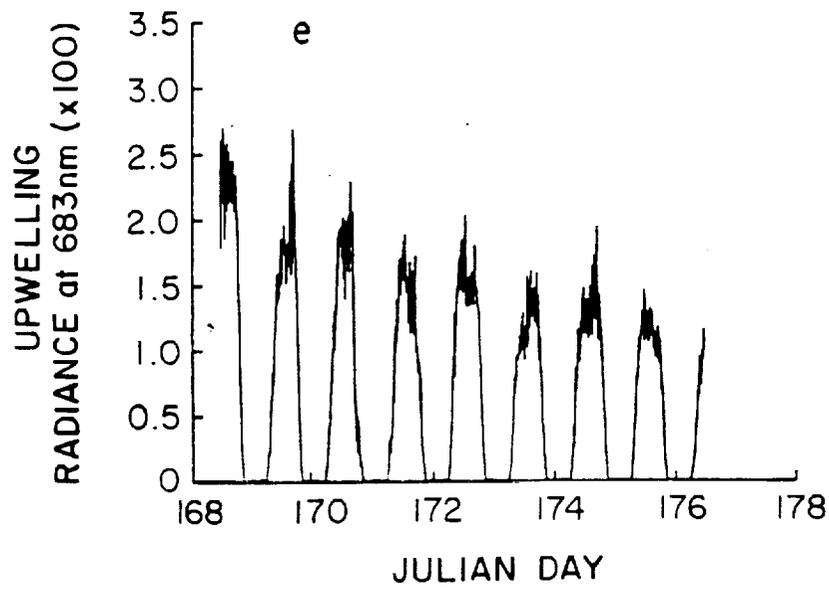
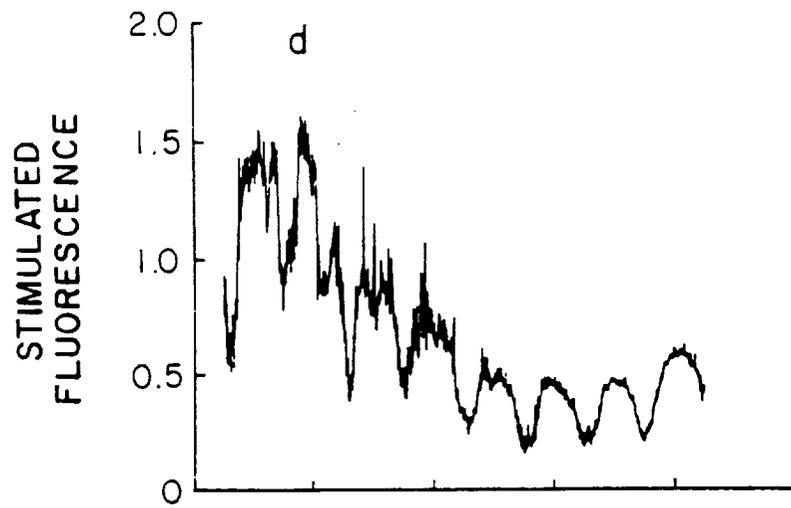


Figure 7. Time series of variables obtained from a Tri-Star drifter including (a) temperature ( $^{\circ}\text{C}$ ) (+ indicates measurements made with thermistor mounted in surface transmitter package), (b) downwelling spectral irradiance at 520nm in  $\text{mW cm}^{-2} \text{nm}^{-1}$ , (c) beam attenuation coefficient in  $\text{m}^{-1}$ , (d) stimulated chlorophyll fluorescence (volts), and (e) upwelling spectral radiance at 683nm in  $\text{W cm}^{-2} \text{nm}^{-1} \text{sr}^{-1}$  (after Abbott et al., 1990).



# DUPLEX COMMUNICATIONS EXPERIMENT

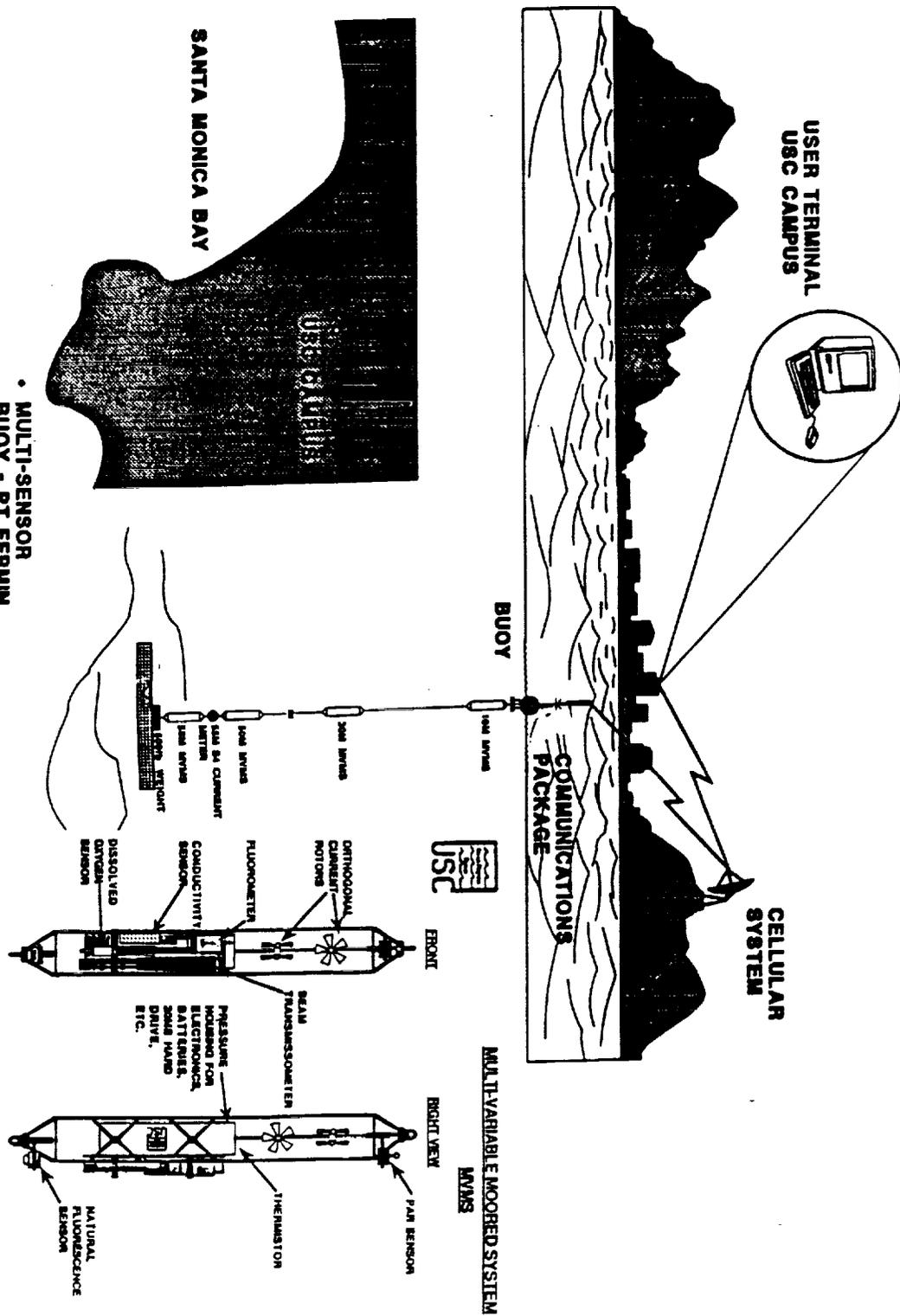


Figure 8. Schematic of interdisciplinary mooring study done off the coast of Los Angeles in 1991. The multi-variable moored system (MVMS) is shown bottom right. Data were recorded internally on disk drives and telemetered to shore (e.g., University of Southern California (USC) in January and February, 1992; see Fig. 9).

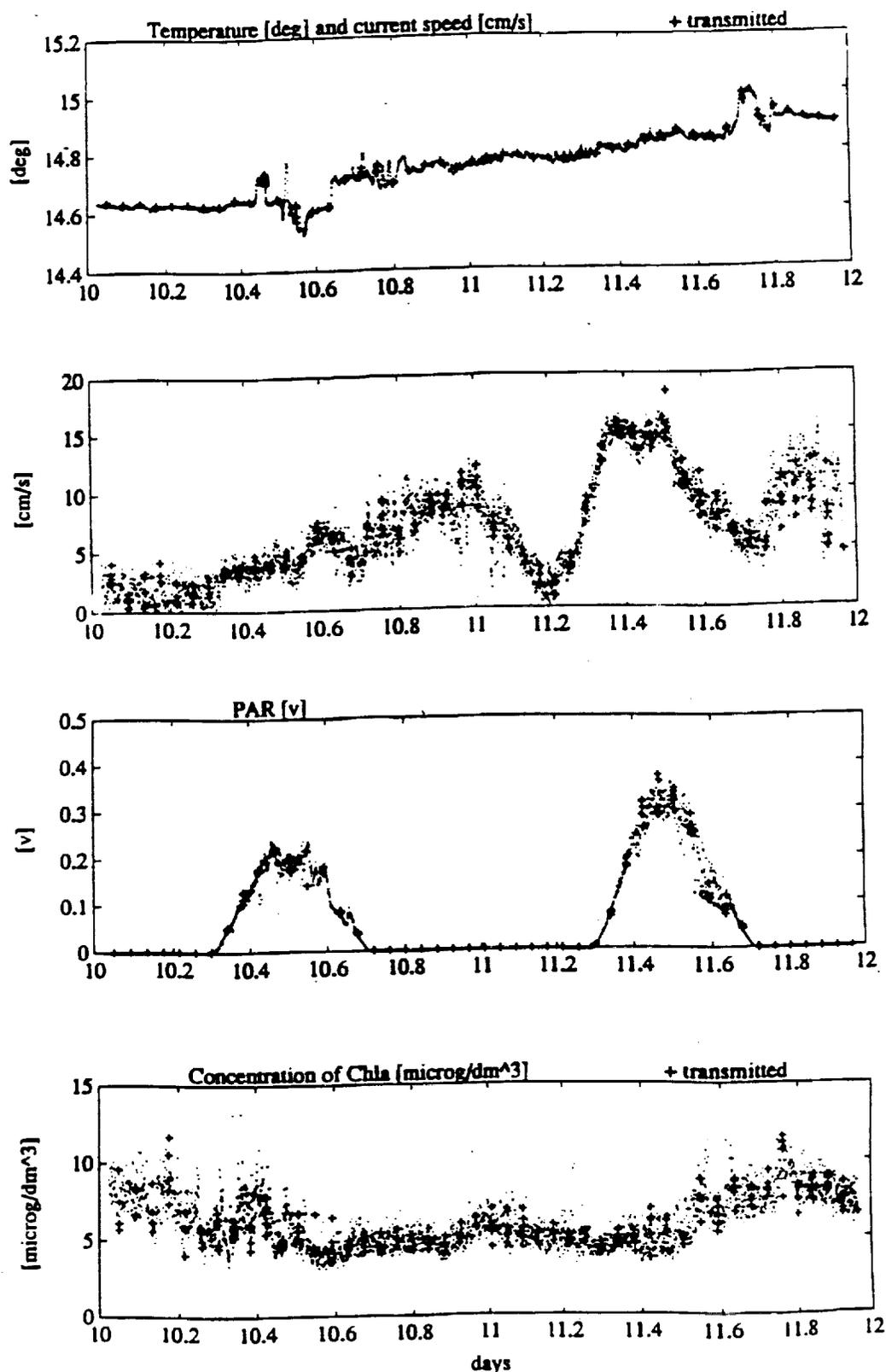


Figure 9. Time series data taken off the coast of Los Angeles (as shown in Fig. 8). Data shown are from the 10m MVMS (Fig. 8) during January 10-11, 1992. Variables (from top to bottom) include: temperature, current speed, photosynthetically available radiation (PAR), and chlorophyll fluorescence. Dots indicate data stored internally and crosses indicate telemetered data.



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## **Wrap-Up Session**

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*Convener - Geoffrey Holland*

